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PLASMA CATHODE FOR E-BEAM LASERS

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Hughes Research Laboratories

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The objective of this program is to develop the plasma cathode electron gun and to demonstrate that it has properties that make it suitable for application to E-beam lasers. The source of electrons in this new and advanced electron device is a plasma generated within a low-voltage hollow-cathode discharge; a thermionic emitter is not required. Electrons extracted from the plasma pass through a triode-type control grid structure and are accelerated to high energies in a

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Many of the basic characteristics of the plasma cathode E-gun concept have been demonstrated with devices producing beams of up to 150 cm^2 in area at beam energies of 150 kV, and at pulsed current densities of 60 mA/cm^2. At lower voltages, pulsed and cw current densities of up to 1 A/cm^2 and to 1 mA/cm^2, respectively, have been obtained. The current density has been found to be uniform to within typically ±5 to 10%, and it has been verified that the beam is monoenergetic. Furthermore, scaling has been demonstrated in a 200-cm long cylindrical discharge device, and a compact high-voltage feedthrough design has been perfected which is applicable to large-scale devices. Two compact, high-voltage plasma cathode E-guns have been designed and fabricated — one with a 4 x 40 cm beam area and the other with a beam area of 5 x 125 cm.

Three major areas of recent work include (1) evaluation of the 5 x 125 cm E-gun under cw CO_2 laser operating conditions. This gun has been operated for six months with highly satisfactory results. The beam energy was 140 to 150 keV with an average beam current through the foil of 0.1 mA/cm^2. The beam uniformity was 10 to 15%. Some arcing was encountered that will require minor modifications. (2) Beam uniformity studies with the 4 x 40 cm E-gun are in progress which are designed to obtain a better understanding of variations in electron beam current density. (3) An integral plasma gun laser was also studied. An analysis was made of a low pressure laser which is excited by an electron beam with energies in the range of 1 to 10 kV. No foil window is required and the laser is scalable. However, an analysis of the argon ion laser indicates that the efficiency will be low.

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SUMMARY

The objective of this program is to develop the plasma cathode electron gun and to demonstrate that it has properties which make it suitable for application to E-beam lasers. The source of electrons in this new and advanced electron device is a plasma generated within a low-voltage hollow-cathode discharge; a thermionic emitter is not required. Electrons extracted from the plasma pass through a triode-type control grid structure and are accelerated to high energies in a plasma-free region prior to emerging from the gun through a thin foil window. The device, which is capable of both pulsed and cw operation, is characterized by durability, low cost, low power consumption, minimal pumping requirements, small size, and fast turn-on in comparison to thermionic E-guns.

Many of the basic characteristics of the plasma cathode E-gun concept have been demonstrated with devices producing beams of up to 150 cm^2 in area at beam energies of 150 kV, and at pulsed current densities of 60 mA/cm^2. At lower voltages, pulsed and cw current densities of up to 1 A/cm^2 and to 1 mA/cm^2, respectively, have been obtained. The current density has been found to be uniform to within typically ±5 to 10%, and it has been verified that the beam is monoenergetic. Furthermore, scaling has been demonstrated in a 200-cm long cylindrical discharge device, and a compact high-voltage feedthrough design has been perfected which is applicable to large scale devices. Two compact, high-voltage plasma cathode E-guns have been designed and fabricated — one with a 4 x 40 cm beam area and the other with a beam area of 5 x 125 cm.

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through the foil of 0.1 mA/cm^2. The beam uniformity was 10 to 15%. Some arcing was encountered that will require minor modifications.

- Beam uniformity studies with the 4 x 40 cm E-gun. Tests are in progress which are designed to obtain a better understanding of variations in electron beam current density.
- Integral plasma gun laser. An analysis was made of a low pressure laser which is excited by an electron beam with energies in the range of 1 to 10 kV. No foil window is required and the laser is scalable. However, an analysis of the argon ion laser indicates that the efficiency will be be low.

I. INTRODUCTION

The plasma cathode electron gun concept has been developed to the level of large area, operating, cw electron guns during previous periods of this contract (N00014-72-C-0496). The objectives of the current program are (1) to continue the development of plasma cathode electron gun to optimize the performance characteristics and improve reliability, and (2) to investigate the possibility of an "integral plasma gun laser," in which a low pressure laser may be incorporated into the plasma cathode electron gun and eliminate the need for a foil window. During this reporting period (July through December 1974), the effort was concentrated on three major areas: (1) Testing and modification of a 5 x 125 cm plasma cathode electron gun. This device was designed and fabricated during the previous six months and is the first fully operating plasma cathode electron gun. Operation of this gun has been very successful, but numerous minor problems were encountered, requiring changes in design or operating procedures. (2) Continued testing of the 4 x 40 cm electron gun. This gun is a compact high voltage experimental device which was previously used to test many of the design features incorporated in the 5 x 125 cm gun. During this reporting period studies have been made of the uniformity of the electron beam current density in cw operation. (3) Analysis of the integral plasma gun laser concept. Calculations were made of the potential efficiency of an argon-ion integral plasma gun laser.

The basic concepts of the plasma cathode electron gun and a summary of previous accomplishments are reviewed in Section II for completeness. Sections III and IV of this report describe the recent results on the 4 x 40 and 5 x 125 electron guns, respectively. Section V contains a description of the integral plasma gun laser concept and the results of the analysis of the argon-ion integral plasma gun laser. Section VI is a summary and discussion of future plans.

II. PLASMA CATHODE CONCEPTS AND PREVIOUS ACCOMPLISHMENTS

This section describes the basic concept of the plasma cathode electron gun and outlines the experimental program performed up to the beginning of the subject reporting period.

A. Basic Concept

A schematic diagram of the plasma cathode electron gun is shown in Fig. 1. The device consists of three major regions: (1) the plasma generation region in which the beam electrons originate, (2) the extraction and control region where electrons are extracted from the plasma and transported in a controlled manner into the acceleration region, and (3) the high-voltage acceleration region where the electrons are accelerated to high energies prior to passing through a thin metal foil window and into the laser medium. These regions are comparable to the thermionic cathode, control grid, and grid-to-anode space of a conventional triode.

The plasma generation region in the present device consists of a low-pressure glow discharge struck between the cold, hollow cathode surfaces and the anode grid, G1. This type of discharge has been chosen because of its stability, reliability, simplicity, and ability to operate at the low gas pressures required to preclude gas breakdown in the acceleration region. In the present application, the discharge operates at a voltage, which is approximately independent of current, of typically 500 to 800 V with helium at pressures typically in the range of 20 to 50 mTorr. Helium is used because He^+ ions have relatively low sputtering yields and because it has high-voltage breakdown characteristics which are superior to those of other gases.

The major characteristic of the hollow cathode discharge is that most of the plasma volume is surrounded by the cathode surface. The discharge, which is sustained by secondary electron emission due to ion bombardment of the cathode surface, is operated in a region where the rate of ion generation by ionization in the discharge volume is sufficient to maintain the plasma potential slightly above anode

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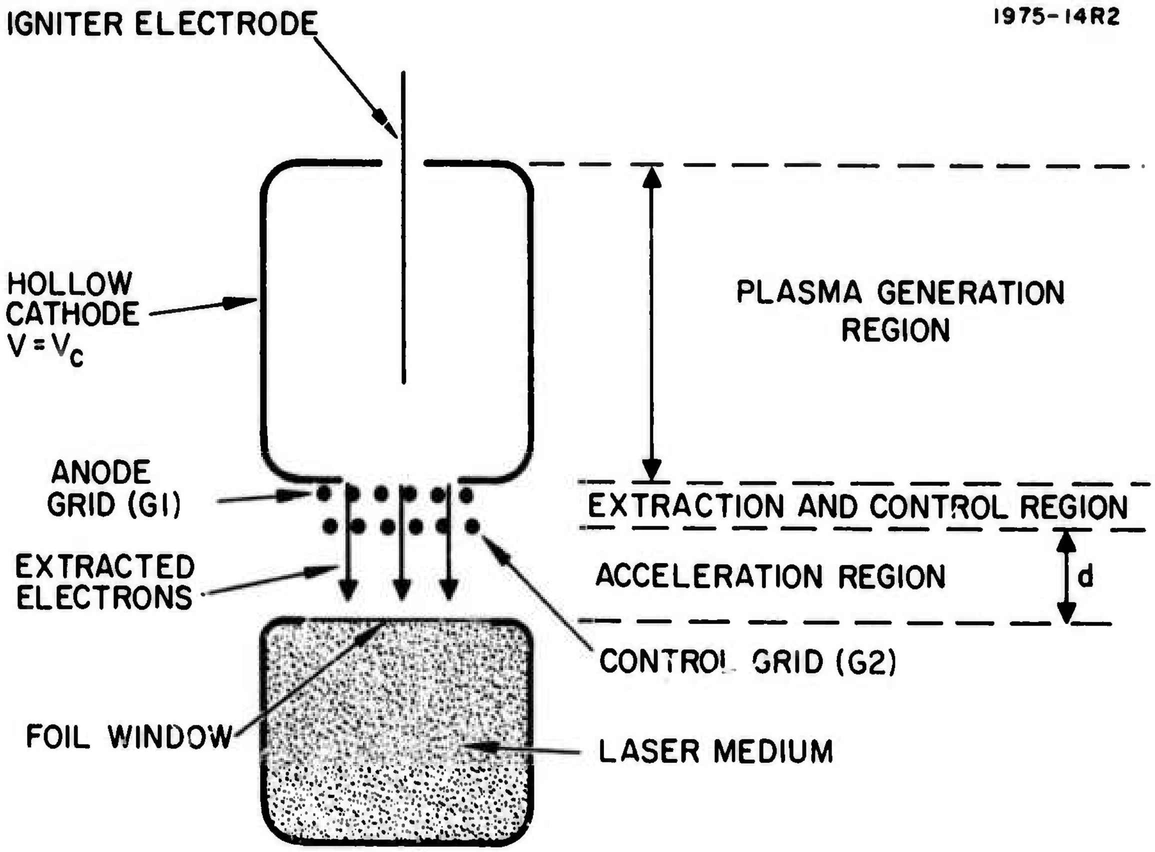

Fig. 1. Schematic of the plasma cathode electron gun.

potential. Because of the large cathode-to-anode area ratio, most ions leaving the discharge are accelerated through the cathode sheath, and utilized with maximum efficiency for secondary electron production, thus minimizing the rate of ion generation required per emitted electron. Furthermore, the secondary electrons accelerated back through the cathode sheath are repeatedly reflected from opposing cathode surfaces. This results in a high probability for making ionizing collisions at low gas pressures where the electron ionization mean-free path exceeds the dimensions of the discharge. At sufficiently low pressure, however, the ionization probability drops to a level for which the discharge cannot be maintained. This determines the minimum working pressure.

Electrons are extracted from the discharge plasma through the anode grid, G1, and pass through the control grid, G2, into the acceleration region. Voltages of typically 0 to -100 V relative to G1 are applied to G2 in order to control the beam intensity from maximum to near cutoff. Grid G2 also serves to provide isolation between the low-voltage discharge region and the high-voltage acceleration region. Alternately, control of the beam current is possible through variation of the hollow cathode discharge current through the potential of G1.

Width d of the acceleration region is critical to the successful operation of the plasma cathode electron gun, since the entire electron acceleration voltage is applied across this gas-filled gap. In order to avoid breakdown in this region, width d must be maintained at a value larger than that which would result in vacuum breakdown, and smaller than the value which would result in Paschen breakdown. Figure 2 illustrates this situation for a gas pressure of 50 mTorr. Both breakdown curves represent conservative values based on data generated in our experiments and quoted in previous literature.

As seen from Fig. 2, there is a region between the two breakdown characteristics where high-voltage operation is possible without incurring breakdown. In the present work, d is chosen for a given maximum operating voltage (150 to 200 kV) to have the operating point

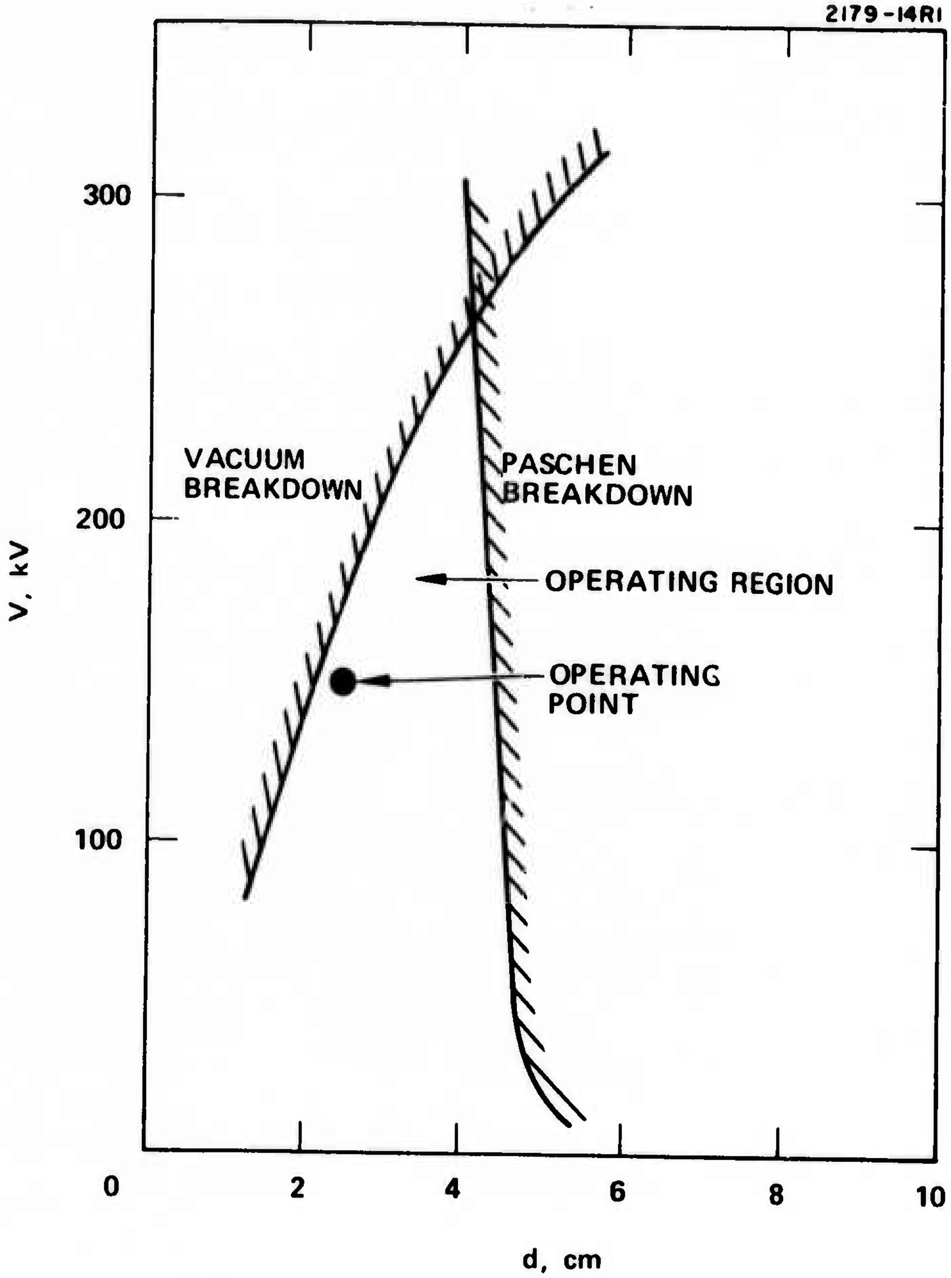

Fig. 2. Low pressure breakdown voltage in the plasma cathode accelerating region as a function of the gap width, d. The Paschen curve is for a pressure of 50 mTorr.

nearer to vacuum breakdown characteristic than the Paschen breakdown curve. This is desirable since this characteristic is expected to be more stable in time than the Paschen curve which is sensitive to the presence of outgassing products. As can be seen from the figure, this design is conservative and accelerating voltages of up to 250 kV may be possible with a helium pressure of 50 mTorr; even higher voltages may be possible at lower pressures.

Figure 3 summarizes the voltage and current requirements for the plasma cathode E-gun which are based on data obtained under typical pulsed and cw operating conditions. The current level of 2 I_B supplied by the high-voltage source assumes a transmission of 50% for the foil window assembly. Measurements on existing plasma cathode devices indicate that the discharge anode current is about equal to the beam current incident on the foil window structure. Therefore, the discharge power supply also operates at 2 I_B in either pulsed or cw mode, depending on the desire application. As is shown, the control grid operates at a slightly negative potential relative to the anode and collects a current of ~15% of the extracted current. The igniter, which provides the background ionization to permit initiation of the hollow cathode discharge without requiring excessive voltages, operates cw at typically 10 mA and 300 V.

B. Previous Development

The basic ingredients of the plasma cathode E-gun development program prior to the subject reporting period are outlined below.[1]

1. Beam Generation — Electron beams 150 cm^2 in area were produced at energies of 150 keV and current densities of 60 mA/cm^2 in 100 μsec pulsed operation. In other tests at lower voltages, pulsed and cw current densities of up to 1 A/cm^2 and 1 mA/cm^2, respectively, were measured. All of these data were obtained with a solid collector plate in place of the foil window.

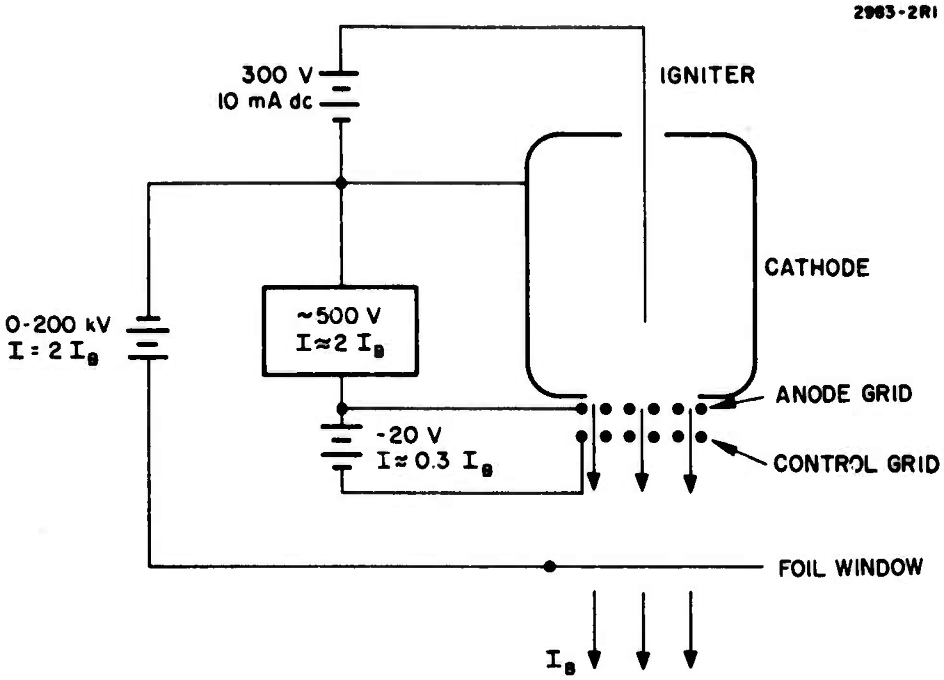

Fig. 3. Plasma cathode power supply schematic.

2. Current Density Distribution — Measurements obtained with a 10 x 15 cm plasma cathode E-gun demonstrated current density distributions uniform to ±5%. Similar measurements, under both pulsed and cw operating conditions, with a low-voltage 4 x 40 cm device indicated uniformities of ±5% and ±10% in the long and short dimensions respectively. Various designs for field shaping electrodes and discharge partitions to influence the distribution were evaluated.

3. Electron Energy Distribution — A retarding Faraday probe was used to measure the electron energy distribution of a small portion of the beam. The energy spread was measured to be monoenergetic to within ±1.4%. The actual energy spread is expected to be less than these measurements indicate on the basis of instrumentation effects. In addition, transmission measurements through a 0.00125-cm thick titanium foil, in combination with calculated transmissions as a function of electron energy, verify that the beam is monoenergetic.

4. Development of Scalable Designs — A coaxial E-gun configuration was developed which readily permits scaling to large dimensions. A 15-cm diameter, 200-cm long cylindrical hollow-cathode discharge with four electrically isolated anode sections was operated. These tests indicate that good (better than ±5%) macroscopic uniformity is achievable provided the anode sections are separately ballasted with resistors of equal value which consume less than 10% of the total low-voltage discharge power. A compact high-voltage feedthrough, which operates under the simultaneous constraints of vacuum, Paschen, and dielectric bulk and surface breakdown, was developed and successfully tested at up to 200 kV.

7. High Voltage, Large Area Plasma Cathode Electron Guns — A 4 x 40 cm and a 5 x 125 cm plasma cathode electron gun were designed and fabricated in compact designs suitable for incorporation into laser systems. These E-guns and their test results are described in Sections III and IV.

III. 4 x 40 CM PLASMA CATHODE E-GUN

The 4 x 40 cm plasma cathode electron gun was designed and built to provide an intermediate size, practical E-gun suitable for evaluations relevant to large-scale devices. In particular, this device was used to develop design data for the 5 x 125 cm E-gun, discussed in Section IV. During this reporting period, efforts on the 4 x 40 cm device were directed toward improving the beam current density distribution and to studies of a new discharge configuration called the Wire Discharge Cathode. The previous work with the low voltage version of this device (Ref. 1) demonstrated a uniformity in the long dimension of ±5%, but beam uniformity measurements on the high voltage gun (described below) indicate a variation in the long dimension of ±20% even under the same low voltage conditions. A brief description of the gun is given below, followed by the results of the recent experiments.

A. 4 x 40 CM E-Gun Design

The design of the high-voltage 4 x 40 cm plasma cathode E-gun has been described previously (Ref. 2). It is based on two proven components — the low-voltage 4 x 40 cm device and the compact high-voltage feedthrough. Figure 4 shows a schematic cross section of the basic coaxial design and Fig. 5 illustrates the layout of the E-gun. The hollow-cathode discharge runs at a voltage, typically 500 V, which is largely insensitive to the discharge current. The operating voltage depends on the helium gas pressure and the presence of contaminants. The anode grid is formed from square, 52% transparent stainless steel mesh having a 0.014-cm wire diameter. The control grid serves to provide electronic beam control and to ensure isolation between the hollow-cathode discharge and the acceleration region. In the present experiments a square stainless steel mesh with the same geometry as that of the anode grid is used. It is spaced 0.8 cm from the anode grid, a distance which is

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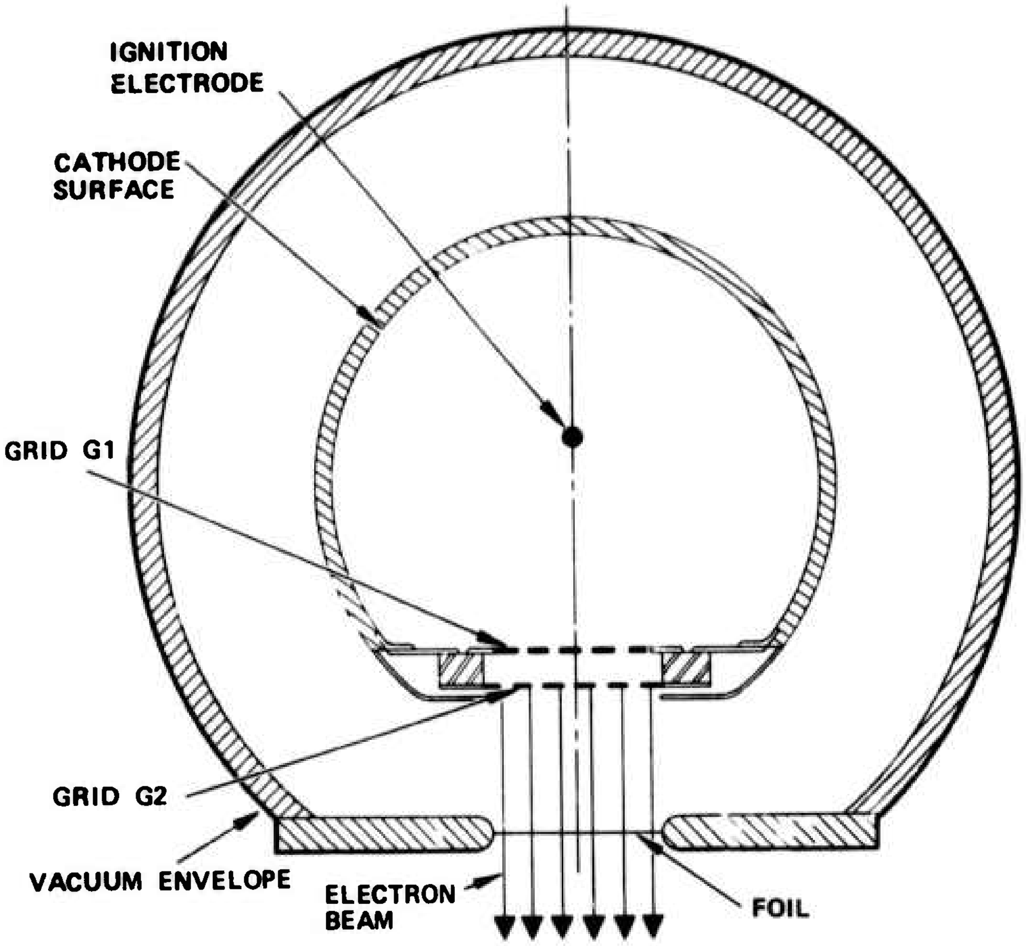

Fig. 4. Cross section of the coaxial E-gun design.

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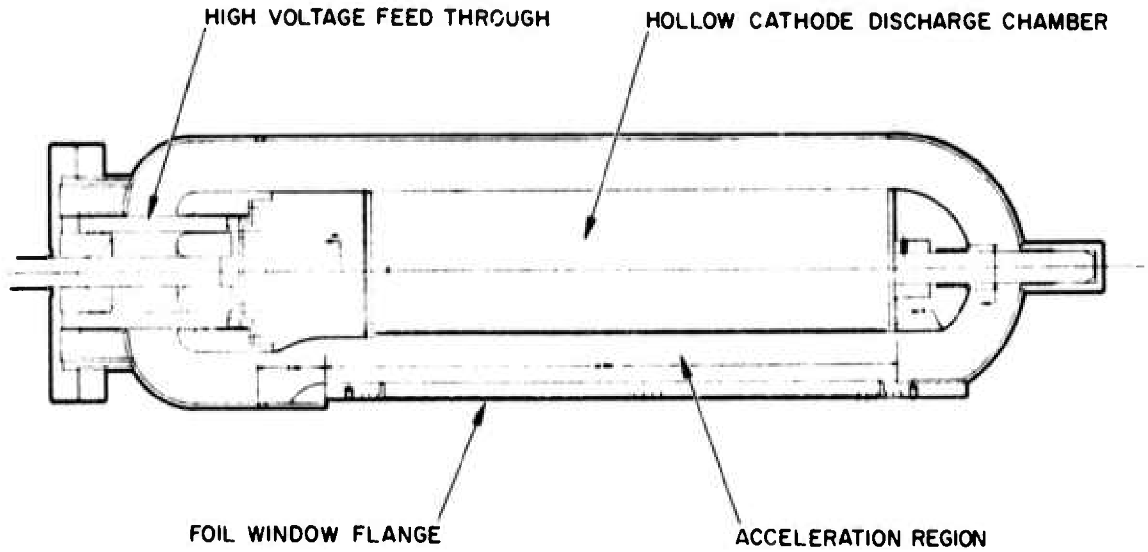

Fig. 5. High energy 4 x 40 cm E-gun.

mechanically convenient and which should not be critical. The hollow cathode discharge supplies an emission limited beam and control is achieved by reverse biasing the control grid so as to retard electron motion through it.

The inner and outer cylinders (refer to Figs. 4 and 5) are contoured so that a spacing of approximately 4 cm is maintained at all points between the two cylinders. This spacing is chosen assuming a 200 kV operating voltage. With reference to Fig. 2, a smaller gap would result in excessive field strengths which could cause vacuum breakdown. A larger gap would reduce the gas pressure range for which operation would be possible. Maintenance of this spacing is accomplished by the use of field shaping electrodes. Electrodes are provided which extend the plane of the control grid, G2, smoothly into the cylindrical cathode surface. Contoured electrodes are also provided at each end of both the inner and outer cylinders in which to minimize electric field concentrations. All parts of both cylinders are formed from nonmagnetic 304 stainless steel which is electropolished in order to minimize sharp surface protrusions.

Electrical power is supplied to the cathode, anode grid, control grid, and igniter electrode through the high-voltage feedthrough (refer to Fig. 5). This component must operate under the constraints of Paschen breakdown in addition to those associated with the other forms of electrical breakdown usually encountered in vacuum high-voltage feethroughs.

A coaxial cable passes through the center of the assembly to a four-pin connector located within the innermost field shaping electrode. The center conductor of this cable is a copper tube which facilitates routing of four conductors to the connector. The copper tube carries current to the cylindrical discharge cathode. The field shaping electrodes within the ceramic tube are designed so that the electric field lines merge smoothly from the 4-cm gap into the coaxial cable.

B. Experimental Results

The 4 x 40 cm plasma cathode E-gun, which is capable of both pulsed and cw operation, has been operated primarily under cw conditions. All experiments to date have been performed with a solid collector plate in place of the foil window in order to avoid the complications of window heating.

High-voltage stand-off tests, which were performed without beam extraction, demonstrated the capability of the present design to operate at beam voltages up to 200 kV. As the voltage was initially increased some arcing and x-ray emission was observed which decreased in time. The 200 kV level was achieved after 1 to 2 hours of conditioning after tube assembly. When a beam current of 30 mA (0.19 mA/cm^2)* was extracted at up to 162 keV for 5 sec, small arcs (without high voltage power supply overload) occasionally occurred. At a beam energy of 150 keV such occurrences were rare and operation was reliable.

1. Beam Uniformity

Preliminary measurements of the current density distributions were made during the previous reporting period. The variations in current density for the high voltage 4 x 40 cm device were somewhat higher than were observed for the low voltage device, even for the same operating conditions. Measurements across the 4-cm beam width generally indicated a variation of ±10 to 15% compared with previous results obtained with the low-voltage 4 x 40 cm device of only ±10%. Measurements along the long dimension indicate a variation of typically ±20%, compared with the value of ±5% measured with the low voltage device.

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* Although average cw beam current densitites of up to 1 mA/cm^2 have been extracted with the low-voltage version of the present device, the high voltage tests were limited to 40 mA or 0.25 mA/cm^2 by high-voltage power supply constraints.

During this reporting period, work on the 4 x 40 cm E-gun has been primarily directed toward understanding the factors which determine the beam current density distribution. The effects of a number of modifications were studied, including the following:

- Replacing the grid screens (old grids were warped)
- Cleaning the hollow cathode surface
- Adding a full length igniter
- Masking the ends of the discharge anode.

The only modification which had a significant effect was the extension of the igniter to the full length of the hollow cathode (the igniter previously extended only 10 cm for the high voltage 4 x 40 cm gun (but had been full length for the low voltage gun). This resulted in a long dimension beam uniformity of ±15%.

To provide better access to the hollow cathode discharge, a bell jar vacuum apparatus has been assembled. The hollow cathode from the 4 x 40 cm gun will be operated inside the bell jar, permitting continuous probing of the beam with a single probe and also allowing visual observation of the hollow cathode discharge.

2. Wire Discharge Cathode

Preliminary investigations have also been made with a new type of plasma cathode E-gun, designated the Wire Discharge Cathode (WDC). It employs a plasma generated using a thin-wire, cold-cathode discharge (the igniter discharge) as the source of beam electrons. This discharge can operate at gas pressures an order of magnitude below those necessary for operation of the hollow cathode discharge used in the present plasma cathode E-guns. Paschen breakdown is thereby eliminated as a major design consideration, permitting the use of larger electrode spacings and operation at higher voltage. It should also result in a simpler and less expensive design.

The WDC approach has been tested using a modification of the existing 4 x 40 cm plasma cathode E-gun. Operation at beam energies of 80 keV and beam current densitites of 50 $\mu A/cm^2$ has been achieved. The current density distribution was uniform to ±10 to 20% over the central region of the device. Development of this concept should lead to devices operating in excess of 200 kV, with current densities suitable for cw or long pulse E-beam sustained lasers.

IV. 5 x 125 CM E-GUN DEVELOPMENT AND TESTING

A large, cw plasma cathode E-gun was designed and constructed to evaluate a full scale E-gun for laser applications. The design was based on the requirements of an existing, cw CO_2 laser and on data obtained with the 4 x 40 cm E-gun. The performance goals of the E-gun are listed below.

• Beam Energy	150 to 175 keV
• Average Beam Current Density	0.1 to 0.5 mA/cm^2
• Minimum Operating Time	5 sec
• Beam Dimensions at the Extraction Grid	5 cm x 125 cm
• Beam Uniformity (long dimension)	±5%
• Half-angle of Beam Convergence at Window	$\sim 10^{\circ}$

The beam convergence is intended to help compensate for divergence at the edges of the beam due to scattering by the foil window. Construction of the 5 x 125 cm E-gun was completed near the end of the previous reporting period and the design details and considerations have been reported in Ref. 2. During this reporting period, the gun was tested under laser operating conditions and considerable test data have been obtained. The performance of the gun was moderately successful. Some design and operating problems were encountered, which is not surprising since several major advances in the plasma cathode technology were involved. These include the first extraction of a beam through a foil, scale up in the beam area by a factor of 5, and generation of a focused beam.

A. 5 x 125 CM E-Gun Design

The E-gun design was discussed in detail in Ref. 2. A brief description of the gun is included here for completeness. Figures 6 and 7 show the design layout of the 5 x 125 cm plasma cathode E-gun. The basic design is very similar to that of the 4 x 40 cm device. In the present design, however, the anode-control grid system is curved

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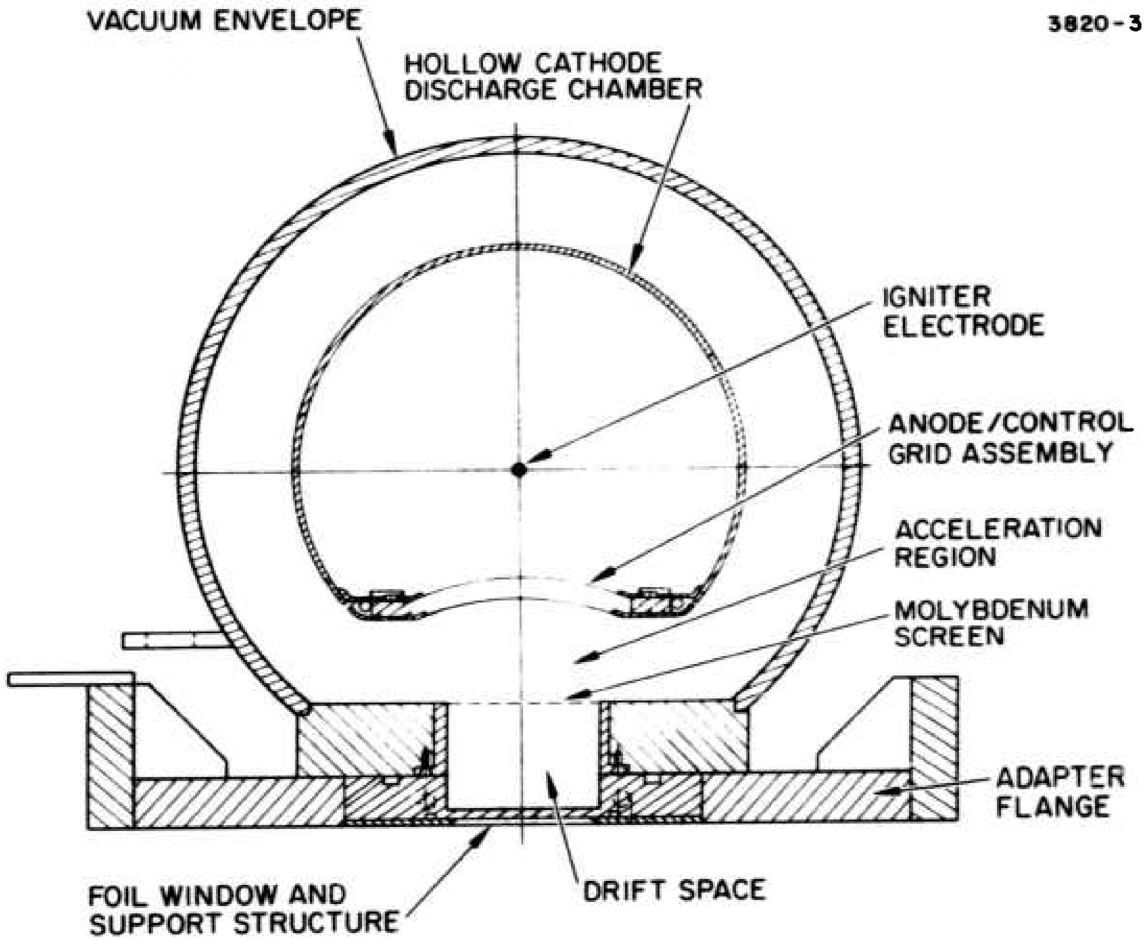

Fig. 6. Cross section of 5 x 125 cm plasma cathode E-gun.

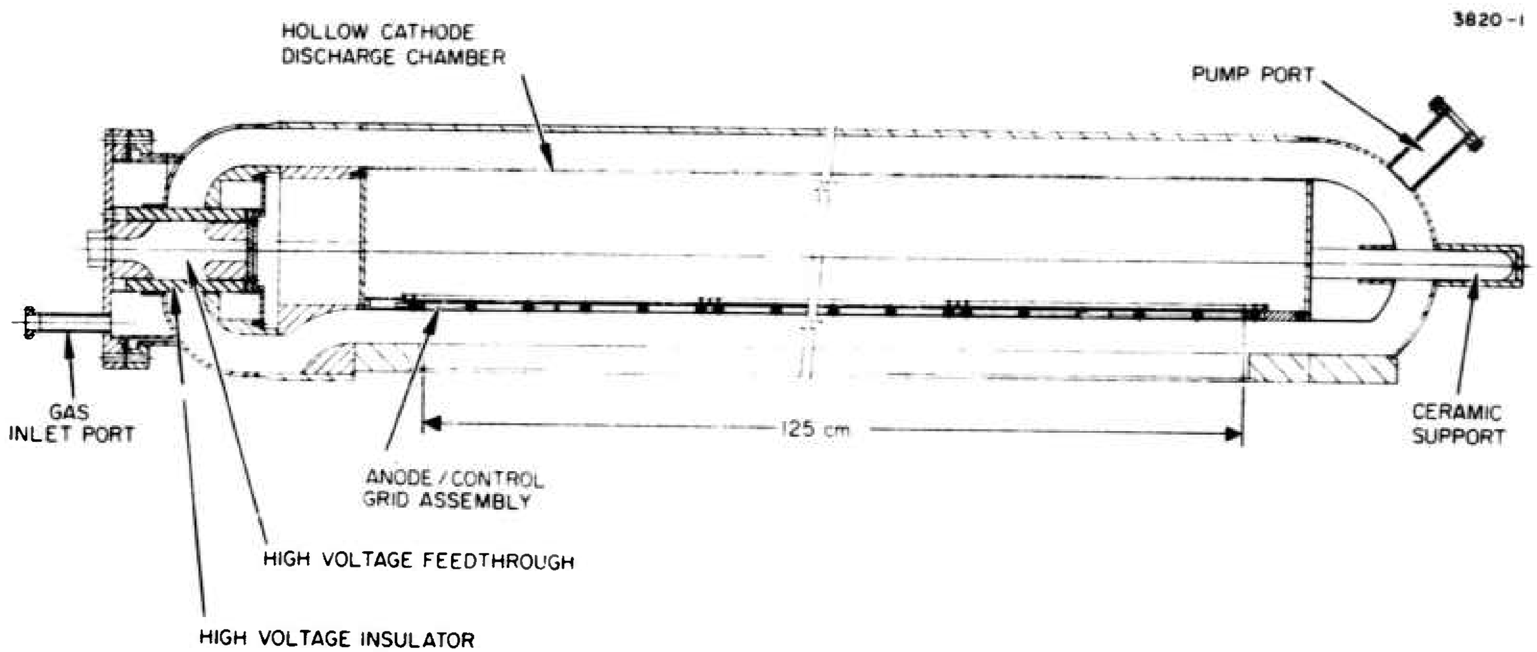

Fig. 7. Layout of 5 x 125 cm plasma cathode E-gun.

in order to provide the desired beam focusing.

The cathode is formed by a stainless steel cylinder of approximately 18 cm i.d. The grid system is supported by brackets attached to this cylinder. The anode and cathode grids have curvatures of approximately 12 and 11 cm, respectively, and are spaced 0.8 cm apart. The grids, which are formed from perforated stainless steel sheet stock 0.095-cm thick with 0.4-cm diameter holes and a transmission of 63%, are covered with 59% transparent stainless steel wire mesh. The perforated material provides mechanical support while the fine mesh, for which the wire spacing of approximately 0.05 cm is less than the Debye sheath thickness, serves to define the plasma boundary. The supporting ceramic pieces are shielded, as in the 4 x 40 cm device, to prevent deposition of sputtered material. A metal tube used to route electrical leads is also included within this shielding.

The spacing between the inner and outer cylinders is maintained at close to 4 cm, thereby resulting in an E-gun outer diameter of 27 cm. In the grid region, this spacing varies from 3.6 cm to 4.5 cm due to the grid curvature. Following acceleration the electrons pass through a potential defining molybdenum mesh (78% transparent) and into a drift region 4.5-cm long. This drift region is necessitated in order to locate the foil window near the lasing medium. The thin foil window is supported against the external atmospheric pressure by a 75% transparent aluminum bar grid structure, which is shown in Fig. 8. The outer diameter of the E-gun is 27 cm.

The high-voltage feedthrough, ceramic support post, and field shaping electrode structures, are similar in design to those of the 4 x 40 cm E-gun. In the present device, due to the somewhat larger gun diameter, the maximum electrical field strengths are 20 to 50% lower than in the 4 x 40 cm device.

On the basis of the results obtained in the previous scaling experiments with the 200-cm long hollow-cathode discharge (Ref. 1), the anode grid is divided into four sections along the length to aid in

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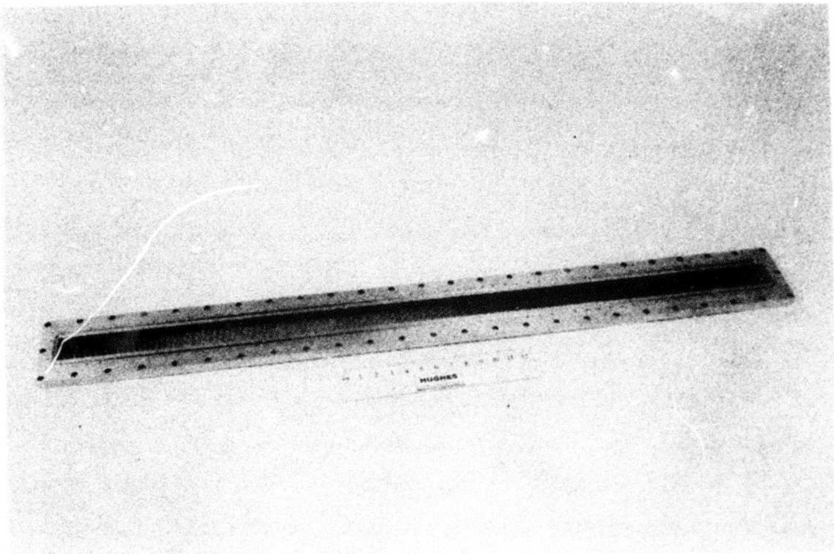

Fig. 8. Foil support structure.

achieving the desired current density uniformity. Each section has a separate ballast resistor located within the vacuum envelope. The control grid is a unipotential surface; this is possible since the previously measured voltage differences between anodes is small -0.1 V. Therefore, the variation in control voltage between anode sections, is not sufficient to cause significant perturbation of the beam current density. The grid system, as well as the foil and flange system, are designed without any major ribs which would shadow the beam.

Figure 9 shows the completed inner cylinder and vacuum envelope. The foil support structure and E-gun adapter flange are not present.

B. 5 x 125 CM E-Gun Performance

The 5 x 125 cm E-gun has been operated over a period of approximately six months, during which tests were made either with a foil window or with a probe plate. In general, the gun performance was highly satisfactory and provided the first demonstration of the plasma cathode as a fully operating, large area, cw E-gun. The major results are summarized below.

5 x 125 CM E-Gun Performance

	Achieved	Goal
Beam Energy	140 to 150 keV	150 to 175 keV
Average Beam Current Density (through the foil)	0.1 mA/cm^2	0.1 to 0.5 mA/cm^2
Beam Uniformity	±10 to 15%	± 5%
Half Angle Beam Divergence	$\sim 10^{\circ}$	10°
Operating Time	-1 sec	5.0 sec

As can be seen, the minimum goals were either met or nearly achieved. Most of the limits on the performance were due to arcing in the gun, which limited the beam energy, average beam current density, and the operating time. With minor modifications, it is expected that

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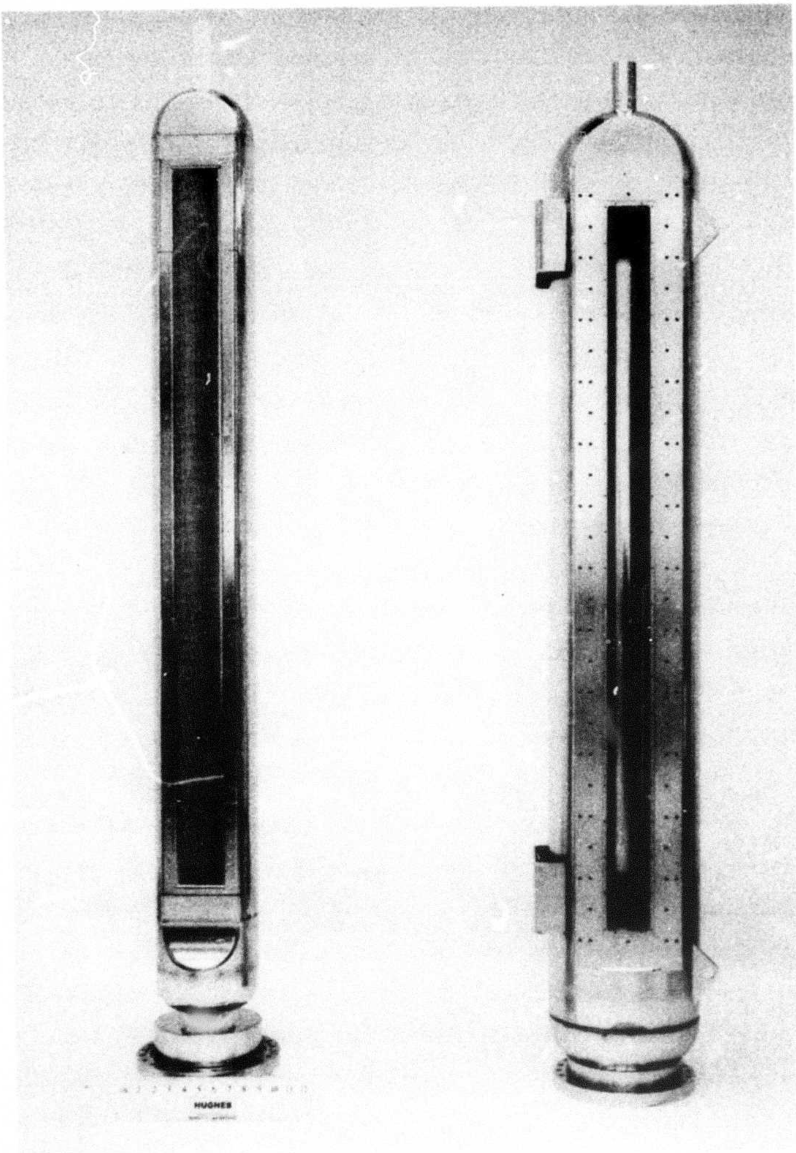

Fig. 9. Inner and outer cylinders of 5 x 125 cm E-gun.

all of the goals will be met. The breakdown is believed to be due to contaminants in the gun, causing Paschen breakdown. A major source of contaminants is probably the foil window which outgasses during operation with a beam. A substantial part of the foil cooling is produced by a high speed flow of laser gas and it is not practical to run the system for long periods to thoroughly process the E-gun and foil window by running the gun. The presence of impurities in the E-gun reduces the breakdown voltage for Paschen breakdown by increasing the total pressure and/or by shifting the Paschen curve to the left (see Fig. 2). Arc marks inside the gun generally occur at positions of maximum gap length (maximum pd) indicating that it is Paschen breakdown. The problem can be solved by improved processing to reduce contamination and/or modifying the gun to operate at lower pressures.

The uniformity of the current density was measured with the probe plate in place of the foil window. The probe plate has fixed current collecting probes spaced at 4 cm intervals along the centerline of the beam. Sets of three probes transverse to the centerline are used to measure the transverse current density distribution. Figure 10 is a plot of typical probe data, showing the longitudinal variation of electron beam current. The upper curves were obtained with a newly cleaned and assembled gun at low voltage (12 kV) and the lower curve was obtained at high voltage (150 kV) after the gun had been operated for several months. The major difference between curves 1 and 2 is that both ends of the beam extraction area were blocked by installing solid metal strips approximately 3 cm wide over the anode grids. The variation in the measured electron current is approximately ±15% for the earlier results and had increased to ±30% after use. The cause of the current density variations is not definitely known. Possibilities are (1) contamination of the cathode surface, producing variations in the secondary electron yield; (2) variations in fields and/or electron transmission at the grids due to misalignment or deformation of the screens. The

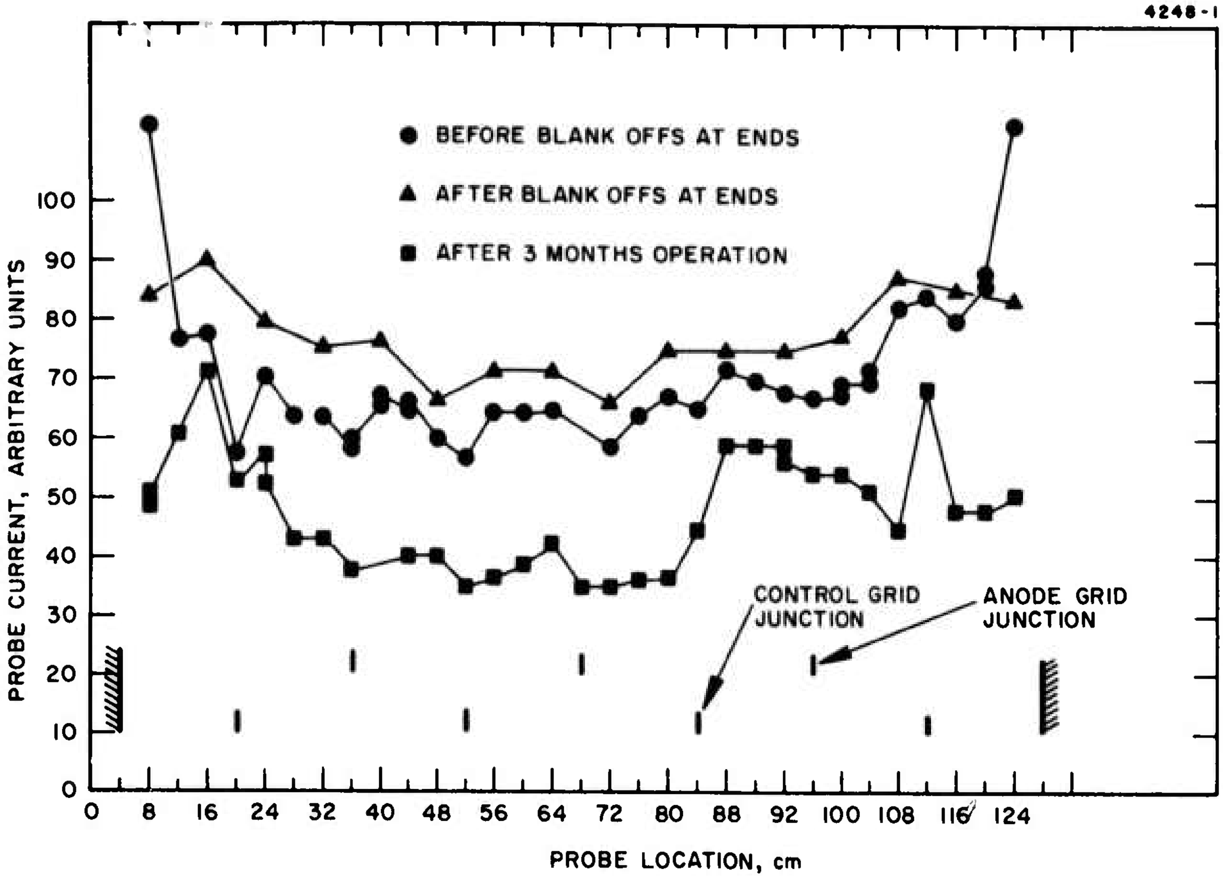

Fig. 10. Longitudinal current distribution in 5 x 125 cm E-gun.

approximate locations of the anodes and control grid sections are indicated at the bottom of the figure, and it can be seen that the major variations occur at or near junctions. The current is uniform over the individual grid sections, suggesting that the variations are caused by grid junctions. However, the variations are no larger than those which occur in the 4 x 40 cm E-gun, which has one-piece grids. The continuing investigations of beam uniformity in the 4 x 40 cm gun are expected to provide information which will lead to improvements in the 5 x 125 cm gun also.

V. INTEGRAL PLASMA GUN LASER

The integral plasma gun laser (IPGL) is a design concept, initiated at the Hughes Research Laboratories, for a new kind of dimensionally scalable pump for some of the low pressure gas lasers. This concept takes advantage of the coincidence of the operating pressures of certain electrically excited lasers (such as noble gas ion lasers and some charge transfer laser systems) and of the plasma cathode electron gun. Because of this coincidence of operating pressures, the need for a foil window is eliminated and the use of (relatively low) electron beam energies of 1 to 10 kV is allowed. This means that the electron beam range in the laser gas medium can be matched to the device dimensions. At the same time, the primary beam energy is high enough to produce a significant number of secondary electrons with energies which can be used to excite laser transitions. This is particularly important, since a single beam electron, with a range comparable to the device dimensions, will produce many secondaries which have short ranges but potentially high probabilities for excitation. The plasma cathode is uniquely suited for this kind of foil-free operation because it can operate in a gaseous environment, where the energetic ion back-bombardment levels are high, without serious degradation. Such operation would not be possible with comparably efficient E-guns employing conventional thermionic cathodes. In the following discussion, the results of calculations for an argon ion laser, employing the IPGL concept, will be presented. This particular kind of laser was chosen for study first because many of the important system parameters are known.

A schematic illustration of the integral plasma gun laser configuration is shown in Fig. 11. The electron gun configuration is similar to that described previously for the high-energy case. However, in this case the foil window, normally employed to isolate the gun region from the laser medium, has been replaced by an entrance

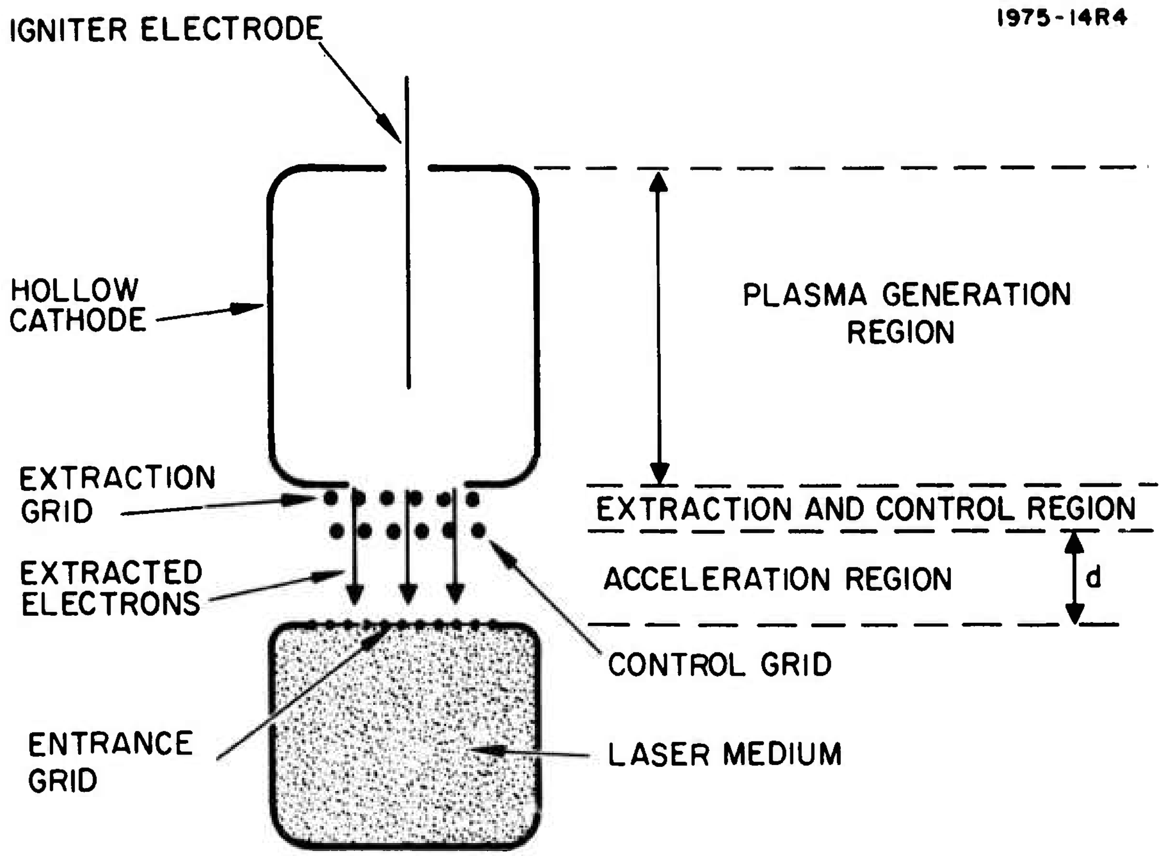

Fig. 11. Integral plasma gun laser.

grid which defines the gap across which the accelerating beam voltage is applied. The maximum allowable operating pressure of a potential device would be determined by the Paschen breakdown characteristic for the gas in question and by the minimum practical acceleration gap width. Using fine-mesh screen grids, and employing standard fabrication techniques, this width would be 1 to 2 mm. For argon gas, these consideration give 0.5 to 1 Torr as the pressure range allowed for 1 to 10 kV beam voltages. The electron range in argon, at these pressures, is about 10 cm at 1 kV to 1 m at 10 kV. For purposes of our calculation, we will assume an argon pressure of 0.5 Torr and a beam voltage of 1 kV.

A primary electron beam at energy E_p and current density J_p will produce a secondary electron charge density at a rate given by

$$\dot{N}_{ST} = N_o \, \sigma_i(E_p) \, \frac{J_p}{e}$$

where

$\dot{N}_{ST}$ = number of secondary electrons produced by ionization of gas atoms/volume/time

N_o = number density of gas atoms

$\sigma_i(E_p)$ = ionization cross section for electrons of energy (E_p)

e = electronic charge.

For a beam voltage $V_p = 1$ kV, $J_p = 100$ mA/cm^2, 0.5 Torr of argon, and with experimentally measured values for σ_i,

$$\dot{N}_{ST} \sim 10^{18}/\text{cm}^3 \text{ sec.}$$

The secondaries have an energy spectrum which has been measured by Ogurtsov[4] and Opal et al.[5] and an approximate analytical expression for the spectral distribution may also be deduced.[5] This analytical expression may then be used to estimate various excitation rates in argon by these secondary electrons.

Excitation processes which may proceed from a collision of a neutral argon atom and a single secondary electron include ionization, excitation of neutral atom excited states, and excitation of singly ionized argon excited states. In this latter case, the cross section for photon emission for several different argon ion laser transitions has been measured[6] and these values include the contributions of cascading from higher lying ionic excited states. For the single-step process, the excitation rate is given by

$$R_x = n_{e_{ST}} N_o \int_o^{E_p} f(E)\,\sigma_x(E)\,V dE$$

where

R_x = number of excitation processes/vol/time for process x (x ~ ionization, neutral excitation, or ion laser line excitation)

$n_{e_{ST}}$ = total number density of secondary electrons

n_o = neutral (argon) atom density

$f(E)$ = secondary electron spectral density function

$\sigma_x(E)$ = cross section for process x

V = velocity of the exciting electron.

A study of the published values for the cross sections for all these single-step processes (σ_x) shows that, in each case, the cross section is large for electron energy values between 30 and 200 eV and that the peak cross section occurs for energies between 50 and 80 eV. Because of this, an approximate expression for R_x is

$$R_x \approx n_{e_1} N_o \sigma_x(\max)\,\overline{V}$$

where

n_{e_1} = number of secondary electrons with an energy between 30 and 200 eV = approximately 3% of the total[4, 5]

$\bar{V}$ = average electron velocity in this range of energies. Of the parameters in this expression, only σ_x (max) varies appreciably so the relative single-step excitation rates will be in the ratio of the cross sections.

In addition to single-step excitation, the ion laser lines may also be excited by collisions between lower energy electrons (18 to 40 eV) and ground state argon ions. For this two-step process, the excitation rate is given by

$$R_{TS} = N_I n_{e_{ST}} \int_0^{E_p} (F(E)\sigma_{TS}(E) V dE,$$

which is similar to the expression for single-step processes except for

N_I = ground state ion population density

σ_{TS} = cross section for excitation by collision of electrons and ions.

An estimate of N_I may be calculated using the ion production rate by primaries ($\dot{N}_{ST} \approx 10^{18}/cm^3$ sec) and the recombination rate in argon ($\approx 10^{-10}$ cm^3/sec)[7] which yields $N_I \approx 10^{14}/cm^3$. The single-step ionization rate due to secondaries will be less than 3% of $\dot{N}_{ST}$ (since n_{e_1}, the fraction of secondary electrons which would be available for ionization is only 0.03) so that the effect of this process will be negligible in determining N_Il. The fraction of secondary electrons with energies between 18 and 40 eV is approximately 0.03 (coincidentally, approximately the same as the fraction with energies between 30 eV and 200 eV) so that the two-step excitation rate

$$R_{TS} \approx N_I n_{e_1} \sigma_{TS}(\max)\ \bar{V}.$$

Hence, a comparison of the single step and two step rates may be made.

The cross-section data for the various processes were obtained as follows:

1. Ionization: W. Lotz, Astrophysical Journal Supp. Series <u>14</u> 207 (1967).

2. Excitation of Neutral Atom Excited States: sum of 13 lines, L. R. Peterson and J. E. Allen, Jr., Chem. Phys. 56 6068 (1972).

3. Single-Step Excitation of Argon Ion Laser Lines: sum of three lines (4965 Å, 4765 Å, 4880 Å) including cascading from higher excited levels. P. N. Clout and D. W. O. Heddle, J. Phys. B4, 483 (1971)

4. Two-Step Excitation of Argon Ion Laser Lines: sum of five lines (4880 Å, 5145 Å, 4965 Å, 4765 Å, and 4579 Å) including cascading. I. P. Zapesochnyi et al., Sov. Phys. JETP 36 1056 (1973); Handbook of Lasers, Chem. Rubber Co., 1971, p. 286.

From these values obtained, relative excitation rates were calculated as shown in Table I.

Table I. Relative Excitation Rates by Secondary Electrons

Ionization	1
Neutral Excited States	0.36
Single Step Excitation of 3 Argon Ion Lines	0.0036
Two Step Excitation of 5 Argon Ion Lines	0.0004

These results are very similar to those calculated and measured experimentally[8] for a conventional argon ion laser operating at a high current density (>200 A/cm^2) and with a high electron temperature (>10 eV). For such conventional argon ion lasers, the power efficiency is significantly less than 0.1%, and similar operating efficiencies could be expected for the IPGL. The main reason why the IPGL does not appear to be a more efficient pumping scheme is that the measured secondary electron spectrum is not significantly different from that of a 10 to 15 eV average temperature Maxwell-Boltzmann distribution. This suggests that for a similar plasma density, the IPGL pumping rates will be very close to that for a high current conventional ion laser operating at similar pressure. What is gained, with the IPGL, is scalability, but it is not clear that this advantage warrants the expense of an experimental effort at this time. Moreover, because all the noble gas ion lasers operate in a very similar manner, the same conclusions made above for argon should apply to the others as well. Charge transfer lasers, such as the He-metal vapor and He-I_2 systems, may be very promising in an IPGL configuration.

VI. CONCLUSIONS AND FUTURE PLANS

During the past six months, a full size (5 x 125 cm) operating plasma cathode electron gun has been demonstrated. This gun has been successfully operated 150 keV with an average cw beam current through the foil of 0.1 mA/cm^2 with a beam uniformity of ±10 to 15%. Improvement in the beam uniformity is expected and experiments on a 4 x 40 cm device are in progress for this purpose.

The concept of a scalable integral plasma gun laser was investigated analytically. The most suitable candidates (on the basis of operating pressure) are the noble gas ions, but analysis of the argon-ion system leads to the conclusion that the limiting efficiency will be too low for practical applications.

A new plasma cathode electron gun, the Wire Discharge Cathode, was conceived and preliminary experiments were conducted. This concept has potential as a simpler, higher voltage device than the present plasma cathode electron gun.

During the next six months of this program, the effort will be directed toward the following areas:

- Continued electron beam uniformity studies on the 4 x 40 cm E-gun.
- Investigation of other potential integral plasma cathode laser materials.

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REFERENCES

1. J. R. Bayless, "Plasma Cathode for E-Beam Lasers," Semiannual Technical Report, Contract N00014-72-C-0496, Hughes Research Laboratories, Malibu, California, January 1974.

2. Ibid., July 1974.

3. W. Lotz, "Electron-Impact Ionization Cross Sections and Ionization Rate Coefficients for Atoms and Ions," Astrophysical Journal Supplement Series, Vol. 14, pp. 207-238, May 1967.

4. G. N. Ogurtsov, "Energy Distribution of electrons emitted by Argon Atoms Under Electron Impact," Sov. Phys. JETP 37, 584-586, October 1973.

5. C. B. Opal, W. K. Peterson, and E. C. Beaty, "Measurements of Secondary-Electron Spectra Produced by Electron Impact Ionization of a Number of Simple Gases," J. Chem. Phys. 55, 4100-4106, 15 October 1971.

6. P. N. Clout and D. W. O. Heddle, "Electron Impact Excitation of Argon II Lines," J. Phys. B 4 483-493 (1971).

7. S. C. Brown, Basic Data of Plasma Physics (MIT Press, Cambridge, Massachusetts, 1959), p. 195.

8. V. F. Kataeva, A. N. Odintsov, and N. N. Sobdev, "Continuously Operating Argon Ion Lasers," Sov. Phys.-Uspekhi 99, 699-730 (1970).

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